ANALYSIS AND DEVELOPMENT OF HEURISTIC STRATEGIES IN HEAT EXCHANGER NETWORK SYNTHESIS

by

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In memory of my late father-in-law,

Mr. Shiwei Wu,

to whom this work is dedicated.

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CHAPTER 1

INTRODUCTION

1.1 PROCESS SYNTHESIS

Process design, beginning with selection of a chemical reaction or reactions and finishing with equipment sizing and estimation of the total cost, is a creative process. It involves four stages: synthesis, analysis, evaluation, and optimization. Its first stage, process synthesis, is concerned with invention of the structure or flowsheet of the process under design. The following definition appears to be generally accepted for process synthesis (Westerberg, 1987): "It is the discrete decision-making activities of conjecturing: (1) which of the many available component parts one should use, and (2) how they should be interconnected to structure the optimal solution to a given design problem."

Although process synthesis resorts to numerous scientific and mathematical principles, it is, in reality, an artistic activity. The procedure for process synthesis appears to be similar to that of pencil-sketching by an artist, in which all but the most significant details of the design are suppressed. At this stage of design, only

the most important technoeconomic tradeoffs are identified. The designer generates one or more process alternatives, some of which are evaluated to be optimal and selected for subsequent modifications. Obviously, not only depthwise but also breadthwise knowledge of the process under design are required for successful execution of the task.

It should be emphasized that even when the synthesis targets of a process system are specified, its structure and the performance of its processing units are not uniquely determined. Process synthesis almost always involves solution of a large combinatorial problem. This arises from the fact that usually numerous feasible processing schemes can attain the same design objectives. Heat exchanger network (HEN) synthesis is a typical example. For instance, even a relatively simple case of three cold streams and two hot streams leads to 847 alternative heat exchanger networks if stream splitting and multiple matchings of streams are not permitted (Westerberg, 1980). Since industrial processes, more often than not, may involve more than 10 streams, the number of feasible networks is essentially countless if stream splitting and multiple matchings are allowed. The combinatorial characteristics of process synthesis impose an excessive computational burden in evaluating the performances of all feasible alternatives in selecting the

most attractive design. In practice, therefore, process synthesis is an act of quickly determinating the optimal process structure, i.e., the optimal interconnection of process units.

The research efforts in process synthesis have been directed towards evolving the basic principles and axiomatic systems for synthesis and towards formalizing of synthesis methodologies. Obviously, the quality of the resultant structure at the synthesis phase is mainly limited by the quality of the basic concepts. Therefore, how to formalize the domain knowledge and how to utilize the basic concepts rationally are the keys to the efficacy of synthesis.

The entire process synthesis can be decomposed into several subproblems (see, e.g., Nishida, et al., 1981). These are syntheses of reaction paths, reactor networks, separation systems, heat exchanger networks, control systems, and entire process flowsheets. Substantial progress has been made in the last two decades to solve these subproblems. Among them, heat exchanger network synthesis has the most impact in industry; this is mainly due to the enomous economic benefits derived from energy integration in various process plants, such as refineries, hazardous waste incineration plants and power plants.

1.2 HEAT EXCHANGER NETWORK SYNTHESIS

Masso and Rudd (1969) were among the first to systematically attempt heat exchanger network (HEN) synthesis; since then, numerous methods have been developed. The HEN synthesis is traditionally carried out under steady-state condition. Nevertheless, the recent emphasis has been on the consideration of the effect of dynamic characteristics on the operability of the resultant network.

1.2.1 Problem Specification

A HEN synthesis problem can be stated as follows (see, e.g., Masso and Rudd, 1969; Pho and Lapidus, 1973; Grossmann and Sargent, 1978; Papoulias, 1982; Liu, 1987):

There is a total of N_h hot streams to be cooled and N_c cold streams to be heated. Associated with each stream are its source temperature T_i^s, target temperature T_i^t, and heat capacity flowrate $\dot{M}c_{p_i}$. Moreover, N_{hu} heat-utility streams and N_{cu} cooling-utility streams are available. The synthesis problem is to create one or more optimum or at least near optimal networks of heat exchangers, heaters and

coolers to attain the specified stream target temperatures. The objective is almost always the minimum annualized total cost of the synthesized network, including the annualized capital cost and the annual cost of utilities.

Even when no chemical reaction and separation are involved, the HEN synthesis is nevertheless a complicated design problem. Consequently, a set of assumptions is almost always imposed to establish the synthesis methodology (see, e.g., Nishida et al., 1981). The most important among them are the assumptions of constant stream source/target temperatures and heat capacity flowrates. These assumptions give rise to the following optimality criteria.

a. The minimum total cost expressed as a mathematical objective function, e.g., the well-known 0.6 power rule (see, Grossmann and Sargent, 1978);

b. The minimum total cost resulting from the minimum utility consumption and the minimum number of heat transfer units (see, Linnhoff et al., 1982).

The minimum utility consumption corresponds to the maximum energy recovery through heat exchange between streams, and the minimum number of heat transfer units corresponds to the minimum investment cost. Unfortunately, these two can

not always be realized simultaneously; a trade-off must be made between them.

In reality, the source/target temperatures of streams and their heat capacity flowrates can vary appreciably. Furthermore, other parameters involved in HEN synthesis, such as heat transfer coefficients and characteristics of utility streams, can vary appreciably. Therefore, other criteria, such as flexibility and resilience, have been considered besides the total cost (see, e.g., Grossmann et al., 1983; Morari, 1983; Colberg and Morari, 1987).

1.2.2 Methodologies of HEN Synthesis

Various methods have been developed for HEN synthesis, which can be roughly classified as algorithmic methods, search methods, targets methods, heuristic methods, and hybrid methods (see, e.g., Umeda, 1983). In this section, the principles behind each method are briefly discussed.

Algorithmic methods. This class of methods is based on the mathematical programming. Nevertheless, it is often extremely difficult, if not impossible, to pose HEN synthesis as a mathematical programming problem, especially when the available information and data are imprecise or when insufficient information and data are available. Among the mathematical programming techniques, the most

frequent choice is the mixed integer nonlinear programming (MINLP) in which structural optimization and parameter optimization are formalized simultaneously (see, e.g., Grossmann and Santibanes, 1980). Unfortunately, it appears that no efficient algorithm exists to solve MINLP problems. The future of HEN synthesis methods resorting to algorithmic optimization has been questioned by several researchers (see, e.g., Stephanopoulos, 1981; Papoulias, 1982).

Search methods. Search is a universal problem-solving mechanism in Artificial Intelligence (AI). By definition, the sequence of steps required for network synthesis is not known a priori but must be determined through systematic trial and error. The techniques used include: breadth-first search, depth-first search, and branch and bound search (see, e.g., Jezowski et al., 1986; Umeda, 1983).

If HEN synthesis is represented as a search tree, its root corresponds to the initial empty network, and the nodes in the last level correspond to the resultant alternative networks; the nodes between the root and the last level correspond to incomplete networks. The breadth-first search generates the nodes of the search tree in order of their distance from the root; while the depth-first search selects the deepest node in the search tree for expansion. The former is regarded as a space-limited

method; and the latter a time-limited method. Although a feasible network can be identified by search methods, its optimality is not guaranteed. Therefore, they are considered to be inefficient.

The branch and bound method is an enumerative or tree search scheme for problem-solving. The utility of this method derives from the fact that, in general, only a small fraction of possible solutions need be enumerated; the remaining solutions are eliminated from consideration through the application of bounds indicating that such solutions are not optimal. The deficiencies of the method include the difficulty involved in correctly setting bounds on the value of the objective function over the subsets of solutions to prevent the loss of optimal solution. To remedy these deficiencies, various new search methods, such as best-first search, A^* algorithm, and iterative-deepening-A^* search, have been developed (see, e.g., Pearl and Korf, 1987).

<u>Target methods</u>. The basic idea underlying this class of methods is to derive targets mainly based on thermodynamics. This enables us to derive targets prior to the network construction. The thermodynamic-combinatorial (TC) algorithm (Linnhoff, 1979) and the pinch design method (Linnhoff, et al., 1982) are the major methods in this

class. In the TC algorithm, the stream/stream match decisions are made simultaneously, while in the pinch design method, these decisions are made sequentially. According to the pinch design method, a HEN synthesis problem is decomposed into two parts at the pinch point where no heat flows in cascade between them. Each part is designed separately, and a complete network is generated by combining the two parts.

Although the target methods generate useful information about targets, they do not provide a systematic procedure for determining the process configurations satisfying the predicted targets. This is the reason why only the target prediction mechanism for these methods has been accepted. The strategies for network invention by the method are yet to be fully developed.

Heuristic methods. Heuristic methods are based on rules of thumb, i.e., heuristics; a heuristic provides a plausible direction in the solution of a problem. It is, however, unjustified and fallible in the final analysis (Koen, 1985). Nevertheless, this class of methods is attractive because at least one near optimal network with relative ease can be identified by resorting to the designer's knowledge of the problem. Moreover, the resultant network can be upgraded rationally.

The heuristic rules associated with a learning technique were first applied to HEN synthesis by Masso and Rudd (1969). The application of this technique is initiated by the development of several sets of feasible heuristic rules. The weighting term or weight assigned to each particular heuristic rule is based on the designer's past experience and/or available information and data. Then the weight is incrementally increased iteratively if its application results in a success; otherwise, it is decreased.

Although numerous heuristics have been developed, and some of them have been incorporated into various search methods, relatively little progress has been made in synthesizing HEN's with these heuristics. The reasons are as follows:

a. Target setting at the preanalysis stage has received undue emphasis. The necessity of developing heuristics for stream match recommendations has almost been totally neglected.

b. Although various heuristics are available at the network invention stage, as summarized by Nishida et al. (1981), no detailed examination of them has been made; in fact, numerous redundancies exist among them.

c. The available heuristics are far from comprehensive and powerful. New heuristic rules, leading

to reduction of the total cost, enhancement of system performance, and minimization of backtracking in network construction, need be developed.

d. Not all heuristics can be represented in terms of heuristic rules. Heuristics consist of heuristic strategies and heuristic rules. The domain knowledge, including the designer's experience, can be divided into five levels in descending order: *linguistic, conceptual, epistemological, logical and physical levels* (see, e.g., Mehta, 1986). The heuristic rules translate the knowledge only up to the *epistemological level*, while the heuristic strategies represent the knowledge at the *conceptual level*. Hence, a sufficient number of heuristic strategies need be developed to minimize excessive loss of knowledge.

Hybrid methods. Hybrid methods combine features of various preceding methods. Since they attempt to take advantage of these features, it appears that most of the existing synthesis methods belong to this class. Currently, significant methods belonging to this class include heuristic search, i.e., depth-first heuristic search or branch-and-bound heuristic search. Mocsny (1986) has stated that some suitable restrictions, which are heuristic in nature, can be applied to HEN synthesis through an algorithmic method.

1.3 OBJECTIVE

The objective of the present work is to lay a groundwork for creating an intelligent knowledge-based system for HEN synthsis. A set of heuristics need be developed systematically for this purpose. In this thesis, currently available heuristic strategies for network invention are exhaustively analyzed; this has led to the elimination of numerous redundant heuristics and to the combination of some. A set of new heuristic rules has been developed to enhance the controllability of the entire network and to reduce the extent of backtracking often required in attaining the optimal network configuration. The effectiveness of this set of rules is demonstrated with several examples. In addition, a set of heuristic rules for stream/stream matching recommendations is also developed, which is important for rapidly identifying the optimal or near optimal solution. These two sets of rules constitute a part of the systematic synthesis strategies of the intelligent knowledge-based system.

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CHAPTER 2

ANALYSIS OF AVAILABLE HEURISTICS FOR NETWORK INVENTION

A heuristic approach for network invention is a stepwise match process generating a network sequentially rather than simultaneously as in an algorithmic approach. In the sequential heat exchanger network (HEN) generation, the initial or preliminary network is obtained at the network invention stage; it is subsequently improved at the network evolution stage. For this two-stage synthesis procedure, the first stage is more important; the initial network can be modified, almost always, only to a limited degree. Therefore, if the heuristics for the first stage are not effective, the initial network in the first stage will be far from the optimal, thereby rendering the modification in the second stage difficult. Thus, care must be exercised to ensure the quality of heuristics for stream/stream matching selection in the first stage.

A comprehensive review by Nishida et al. (1981) contains seventeen heuristics, classified as stream heat selection heuristics (HS-ih/jc where i, j = 1, 2, 3), stream match selection heuristics (HR-1 through HR-4), and stream match restriction heuristics (MR-1 through MR-4). Since then, five additional heuristics have been proposed

(Hesselmann, 1986; Jezowski and Hahne, 1986; Rev and Fonyo, 1986). Two of these are concerned with a pseudo-pinch point situation, while the remaining three are expressed as heuristic functions related to the total cost.

2.1 HEURISTICS FOR STREAM HEAT SELECTION

The first class of heuristics (HS-ih/jc, where i, j = 1, 2, 3) is related with stream heat selection (Table 2-1). There are two groups in this class: one is designated as taking heat, and the other as supplying heat. Between them, nine combinations exist, leading to the following nine rules.

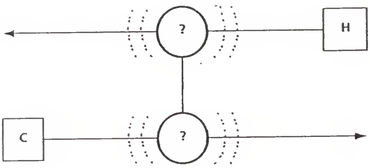
1. Combination of heuristics HS-3h and HS-3c (rule HS-3h/3c).

The rule is to "take heat from the intermediate portion of a hot stream and supply it to the intermediate portion of a cold stream" (Fig. 2-1-a). Two problems arise in applying this rule: the first is in identifying the appropriate locations of a match, and the second is in evaluating the extent of heat exchange through this match. It is extremely difficult, if not impossible, to determine the optimal intermediate portions, i.e., locations, and the extent of heat exchange. The following analysis reveals that, in fact, rule HS-3h/3c is redundant.

Suppose that the extent of heat exchange between hot stream H2 and cold stream C1 and identification of the intermediate portions of these streams have been determined, and that the match is implemented through exchanger 1 according to rule HS-3h/3c (Fig. 2-1-b). This

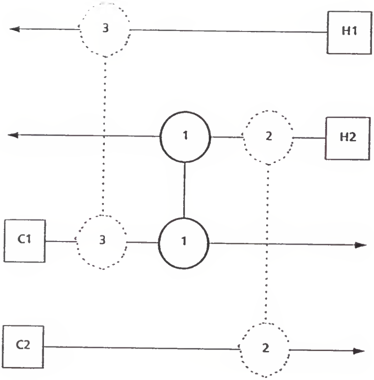
Table 2-1. Stream Heat Selection Heuristics (Nishida et al., 1981)

Take heat		Supply heat	
HS-1h	from the hottest end of a stream	HS-1c	to the hottest end of a stream
HS-2h	from the coldest end of a stream	HS-2c	to the coldest end of a stream
HS-3h	from the intermediate portion of a stream	HS-3c	to the intermediate portion of a stream



(a) HS-3h/3c

Figure 2-1. Replacement of rule HS-3h/3c by rule HS-1h/2c.



(b) HS-3h/3c → HS-1h/2c

Figure 2-1. Replacement of rule HS-3h/3c by rule HS-1h/2c.

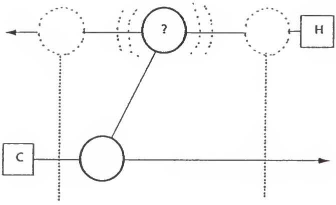
implies that both hot and cold ends of hot stream H2 as well as those of cold stream C1 remain to be matched with other streams. Also suppose that hot stream H2 is next matched with cold stream C2 at their hottest ends through exchanger 2 by resorting to rule HS-1h/1c (Fig. 2-1-b); the first match through exchanger 1 can thus be interpreted as the consequence of applying rule HS-1h/3c. If in a later step, cold stream C1 is matched with hot stream H1 at their coldest ends through exchanger 3 according to rule HS-2h/2c (Fig. 2-1-b), the match through exchanger 1 can be stated as being performed according to rule HS-1h/2c, thereby replacing rule HS-3h/3c in reality. A similar analysis indicates that rule HS-3h/3c can be replaced by rules HS-ih/jc, where both i and j can be 1 or 2, respectively.

It is worth noting that rule HS-3h/3c can be replaced eventually by other rules, and that it is difficult not only to locate the appropriate intermediate portions of the hot and cold streams involved, but also to evaluate the extent of heat exchange. Obviously, we can ignore rule HS-3h/3c from the outset.

2. Combinations of heuristics HS-3h and HS-1c (rule HS-3h/1c), heuristics HS-3h and HS-2c (rule HS-3h/2c), heuristics HS-1h and HS-3c (rule HS-1h/3c), and heuristics HS-2h and HS-3c (rule HS-2h/3c).

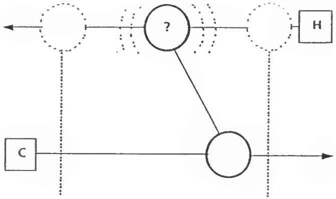
The difficulties arise in determining the extent and location of heat exchange between two streams according to the first two rules, namely rules HS-3h/1c and HS-3h/2c, dealing with heat removal from the intermediate portion of a hot stream. Figure 2-2-a illustrates two cases: one shows that rule HS-3h/2c can be replaced by rule HS-1h/2c if the next match is the one between the hot end of the hot stream and another cold stream, and the other shows that rule HS-3h/2c can be replaced by rule HS-2h/2c if the cold end of the hot stream is next matched with another cold stream. Obviously, if the cold or hot end of a hot stream in Fig. 2-2-b is matched with any other cold stream after the first match according to rule HS-3h/1c, the first match can be replaced by rule HS-2h/1c or HS-1h/1c. Figures 2-2-c and 2-2-d show two other cases where the original matches dealing with heuristic HS-3c are replaced by heuristic HS-1c or HS-2c. Therefore, the nine rules, i.e., rules HS-ih/jc where i, j = 1, 2, 3, are reduced to four rules, i.e., rules HS-ih/jc where i, j = 1, 2. In other words, any combinations involving heuristics HS-3h and/or HS-3c can be neglected. The remaining four rules can still be further reduced by an elimination strategy.

3. Combinations of heuristics HS-1h and HS-1c (rule HS-1h/1c), heuristics HS-1h and HS-2c (rule HS-1h/2c),



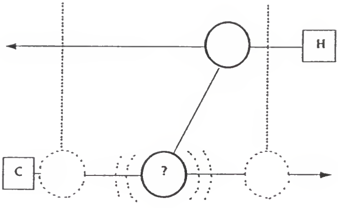
(a) HS-3h/2c ⟶ HS-1h/2c or HS-2h/2c

Figure 2-2. Replacements of heuristic HS-3h by heuristic HS-1h or HS-2h, and of heuristic HS-3c by heuristic HS-1c or HS-2c.



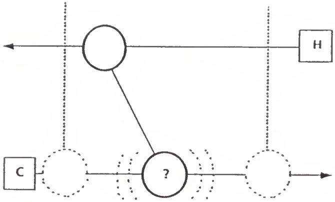
(b) HS-3h/1c → HS-2h/1c or HS-1h/1c

Figure 2-2. Replacements of heuristic HS-3h by heuristic HS-1h or HS-2h, and of heuristic HS-3c by heuristic HS-1c or HS-2c.



(c) HS-1h/3c → HS-1h/2c or HS-1h/1c

Figure 2-2. Replacements of heuristic HS-3h by heuristic HS-1h or HS-2h, and of heuristic HS-3c by heuristic HS-1c or HS-2c.



(d) HS-2h/3c → HS-2h/1c or HS-2h/2c

Figure 2-2. Replacements of heuristic HS-3h by heuristic HS-1h or HS-2h, and of heuristic HS-3c by heuristic HS-1c or HS-2c.

heuristics HS-2h and HS-1c (rule HS-2h/1c), and heuristics HS-2h and HS-2c (rule HS-2h/2c).

The pinch design method appears to be most suitable for determining the minimum energy requirement (MER) and the minimum number of heat transfer units (U_{min}) (see, e.g., Linnhoff and Hindmarsh, 1983). To realize these two design targets, the following elimination strategy has been proposed (Fan and Mehta, 1987).

> *To generate a heat exchanger network featuring the minimum number of heat transfer units, let each match eliminate at least one of the two streams.*

Let us analyze the four rules, namely, rules HS-1h/1c, HS-1h/2c, HS-2h/1c and HS-2h/2c, in the light of this strategy.

In Fig. 2-3-a, the hot end of a hot stream is matched with the cold end of a cold stream according to rule HS-1h/2c. If the heat load of the hot stream, Q_h, is greater than that of the cold stream, Q_c, the cold stream will be eliminated through this match. Note, however, that implementation of rule HS-1h/1c also leads to the elimination of the cold stream as indicated in Fig. 2-3-c,

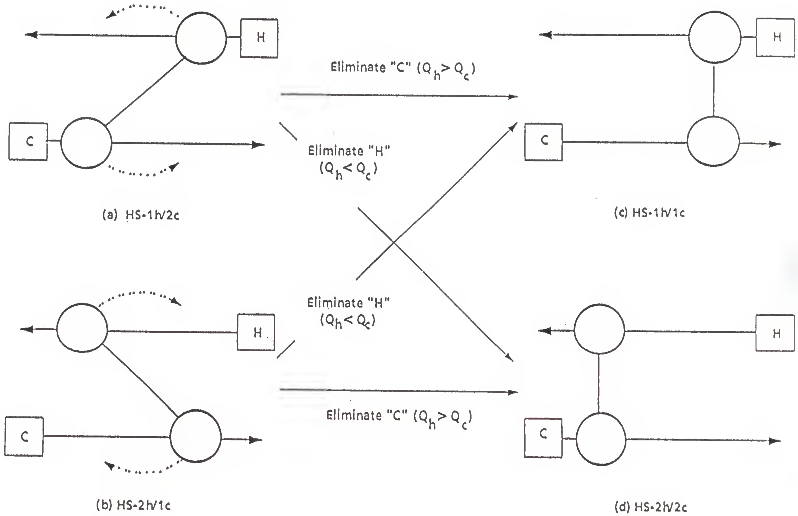


Figure 2-3. Replacements of rule HS-1h/2c by rule HS-1h/1c or HS-2h/2c, and rule HS-2h/1c by rule HS-1h/1c or HS-2h/2c when the elimination strategy is applied.

i.e., if $Q_h > Q_c$, rule HS-1h/2c can be replaced by rule HS-1h/1c. If $Q_h < Q_c$, the hot stream will be eliminated by the match; this is identical to the result from implementing rule HS-2h/2c (Fig. 2-3-d). In other words, rule HS-1h/2c can be replaced by rule HS-2h/2c. Similar analysis can be performed for the match in Fig. 2-3-b where rule HS-2h/1c can be substituted by rule HS-1h/1c or HS-2h/2c, depending on the relative magnitudes of Q_h and Q_c.

We see that only two rules, namely rules HS-1h/1c and HS-2h/2c, remain from the original nine. After renaming them as "hot-end match" and "cold-end match", respectively, these two rules are restated as follows:

Hot-end match:

> *Match the hot end of the residual of a hot stream with the hot end of the residual of a cold stream.*

Cold-end match:

> *Match the cold end of the residual of a hot stream with the cold end of the residual of a cold stream.*

It is worth noting that any of the original streams is regarded as the residual from 0 match.

2.2 HEURISTICS FOR STREAM MATCH SELECTION

The second class of heuristics is concerned with stream match selection; it includes (see, e.g., Nishida et al., 1981):

HR-1: Select a hot stream with the highest source temperature and a cold stream with the highest target temperature.

HR-2: Select a hot stream with the coldest target temperature and a cold stream with the coldest source temperature.

HR-3: Select the match giving the least value to ΔT_{ave}.

HR-4: Select the match giving the least value to the estimated upper bound on the overall network cost.

The first two heuristics, namely heuristics HR-1 and HR-2, are related to the source and target temperatures of streams. These heuristics appear to be meaningful from the standpoint of reducing dead-end situations, thereby minimizing backtracking; however, they are quite fallible. Ponton and Donaldson (1974) have proposed a combined use of heuristic HR-1 and rule HS-1h/1c, or hybrid rule HR-1—HS-1h/1c, leading to an improvement over a synthesis based

only on heuristic HR-1. According to them, solutions with nearly optimum costs can be obtained for pseudo-pinched problems: A pseudo-pinch point exists at one end of the composite curves on the T-H diagram where the temperature difference reaches minimum. Nevertheless, if a problem does not belong to this category, the maximum energy recovery is seldom attained if the synthesis is attempted by resorting to the pinch design method and hybrid rule HR-1—HS-1h/1c. Besides, the resultant structure of the network becomes unduly complicated if the effort is made to maximize the extent of heat exchange at each match in accordance with the elimination strategy (Rev and Fonyo, 1986). More seriously, the resultant network is difficult to improve evolutionarily, since its structure tends to be far from the optimal.

Obviously, the same difficulties mentioned above will arise if a HEN is synthesized with both heuristic HR-2 and rule HS-2h/2c, i.e., hybrid rule HR-2—HS-2h/2c. Therefore, two rules, hybrid rules HR-1—HS-1h/1c and HR-2—HS-2h/2c, are ineffective for the HEN synthesis from the points of view of MER and U_{min}. Furthermore, heuristics HR-1 and HR-2 in isolation are even less useful than the two corresponding hybrid rules. In reality, heuristics HR-1 and HR-2 are contained in rules HS-1h/1c and HS-2h/2c,

respectively. Note that the two heuristics are special cases of the two rules (Fig. 2-4).

If ΔT_{ave} is interpreted as the logarithmic temperature difference in a heat exchanger, the third heuristic, i.e., heuristic HR-3, implies the selection of a match with $\Delta T_{ave,min}$, but such a match leads to neither MER with U_{min} nor reduction in backtracking during the network generation. In addition, it does not take into account other criteria such as system controllability and flexibility.

The last one in the second class of heuristics is heuristic HR-4. This heuristic represents only a general notion; it does not play a role in specifying a match. Thus, it is of limited utility and requires improvement.

The exhaustive analyses of the two classes of heuristics presented in the preceding paragraphs indicate that only two rules derived from these heuristics are significant and useful for synthesis. These two rules are the *hot-end match* and *cold-end match rules* reiterated earlier.

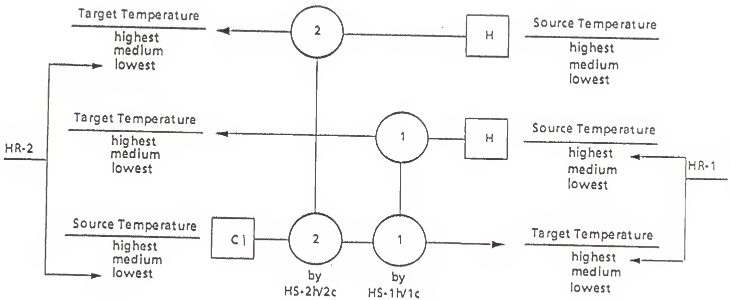


Figure 2-4. Heuristics HR-1 and HR-2: specific cases of rules HS-1h/1c and HS-2h/2c.

2.3 HEURISTICS FOR STREAM MATCH RESTRICTION

Another class of heuristics, i.e., heuristics MR-1 through MR-4, is about stream match restriction. Heuristics MR-1 and MR-2 are the ones disallowing stream splitting and stream/stream rematching, respectively. The traditional view is that stream splitting should be considered only if two constraints, i.e., the MER and the minimum number of heat transfer units under maximum energy recovery ($U_{min,MER}$), will be violated without it, while stream/stream rematching is regarded as a cause of system instability. Thus, stream splitting and rematching should usually be avoided. Nevertheless, it can be demonstrated that stream splitting may reduce the effect of disturbances on the system control performance even if splitting is unnecessary from the MER and $U_{min,MER}$ points of view, and that stream/stream rematching does not always affect the system stability. In other words, the deterioration in the control performance and the instability of the synthesized network are caused only under certain conditions. On the other hand, rematching has the attractive feature of enhancing the controllability and flexibility of the network. Therefore, the match restriction heuristics, i.e., heuristics MR-1 and MR-2, should be reorganized.

One of the remaining two match restrictions, heuristic MR-3, is to disallow a match if it precludes the network from having the minimum utility usage, and the other, heuristic MR-4, is to disallow a match if it precludes the network from having the fewest number of HTU's. While these two heuristics provide broad guidelines, they do not lead to concrete steps for making a match. Since the pinch design method is available, MER and $U_{min,MER}$ can be determined at the preanalysis stage. Then each subnetwork at either side of a pinch point can be designed separately. The pinch design method, along with the elimination strategy and the ability to backtrack, insures that the two goals of synthesis, MER and $U_{min,MER}$, can always be attained, although the total cost of the resultant network may not be minimum.

2.4 HEURISTIC SEARCH APPROACH

The number of recent publication on heuristic strategies for network invention appears to be rather limited (see, e.g., Hesselmann, 1986; Jezowski and Hahne, 1986). Jezowski and Hahne have proposed a heuristic function for match selection based on the well-known 0.6 power rule. A depth-first search approach, incorporating rules HS-1h/1c and HS-2h/2c, is applied to find the solutions with the minimum or near minimum total costs for the eight standard test problems. Hesselmann has presented two new heuristics based on exergetic and cost analyses; the system exergy loss has been introduced as new global information. The networks considered to have near miminum costs have been obtained for the ten standard test problems based on the 0.6 power rule.

Both search approaches, discussed in the preceding paragragh, select a match at each step of synthesis based only on the estimation of total cost. It appears, however, that two deficiencies are inherent in both approaches. The first is that the temperatures and heat capacity flowrates of streams in the synthesized network are inevitably disturbed because of the changes in its operating conditions and economic environment. This may render the network to possess unacceptable operational characteristics

that will eventually be uncovered in the detailed design phase. Hence, the total cost alone should not be the criterion for synthesis. The second is that the approaches can only lead to a single configuration having the minimum or near minimum cost for each problem. Since the cost estimation function is usually not sufficiently accurate, it is extremely arduous to identify the network with the truly minimum cost among several feasible networks having slightly different costs. Many of the well-known test problems give rise to such networks.

A systematic heuristic synthesis approach should not resort solely to a cost estimation function. An ideal heuristic approach should be based not only on the total cost, but also on the system controllability and feasibility.

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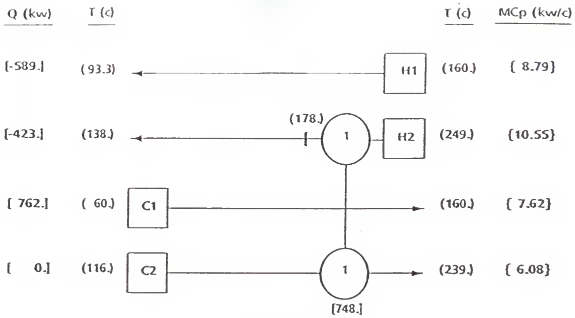
CHAPTER 3

DEVELOPMENT OF HEURISTIC RULES FOR HEN SYNTHESIS

The analysis presented in the preceding chapter has demonstrated that among the seventeen available heuristics, only two are meaningful and necessary for HEN synthesis. These two rules have been restated as the *hot-end match* and *cold-end match rules*; they should be employed in conjunction with the pinch design method and elimination strategy to ensure the attainment of the maximum energy recovery (MER) and the number of heat transfer units less than the minimum number of heat transfer units under maximum energy recovery ($U < U_{min,MER}$). The identification of these two rules reveals that it is necessary to construct the match matrix for the representation of stream matching in HEN synthesis (Fan and Mehta, 1987). A grid diagram representing an incomplete network to illustrate such a scheme is given in Fig. 3-1-a; Figure 3-1-b is the corresponding match matrix. Each row of the matrix contains the match information for a cold stream, and each column for a hot stream; the rows and columns are labeled with the corresponding stream names. Each entry ("box") in the matrix displays the information regarding a match



(a) Grid diagram

	H1	H2	Qc
C1	C *	C H	762.
C2	- -	748.	0.
Cu	C *	C *	250.
Qu	589.	423.	1024.

(b) Match matrix

Figure 3-1. Representation scheme for heat exchanger network synthesis.

between a cold stream and a hot stream; only two possible matches need be considered. One is a match between the hot end of the residual of a hot stream and the hot end of the residual of a cold stream (hot-end match), indicated as "h" at the right-hand side of the box, and the other is a match between the cold end of the residual of a hot stream and the cold end of the residual of a cold stream (cold-end match), indicated as "c" at the left-hand side of the box. A single match matrix is generated for each incomplete network. It must be pointed out that although all thermodynamically feasible match candidates are displayed in the matrix, it does not contain any match decisions. Therefore, a set of rules is required to deal with the total cost, system controllability, and ease of network generation. Moreover, exhaustive analysis of the process data at the preanalysis stage is essential; it gives rise to a set of guidelines for stream/stream matching or match selection. While this has been almost totally neglected hitherto, an experienced designer, in fact, almost always attempts to identify preferred and disallowed matches prior to constructing a network. Obviously, expressing some domain knowledge and designer's experience as heuristic rules will be useful for rapid identification of superior network solutions. This is extremely important for the synthesis of the energy recovery system of a process plant,

e.g., a hazardous waste incineration plant, or the plant in its entirety. For such a plant, the thermal efficiency is of the utmost importance.

This chapter aims at developing heuristic rules for both stream match recommendations at the preanalysis stage and stream match selections at the network invention stage.

3.1 HEURISTIC RULES FOR STREAM MATCH RECOMMENDATION

At the preanalysis stage, a set of heuristic rules for stream match recommendation is generated. The nature of disturbance propagations which might occur in the resultant network should also be examined at this stage.

3.1.1 Requirement for Stream Match Recommendation

As stated in the preceding chapter, the targets of HEN synthesis include a high degree of controllability, in addition to the MER and $U < U_{min,MER}$. Obviously, it is highly desirable that these targets be reached with minimum effort, or specifically, with minimum backtracking. However, the stream match recommendations generated at the preanalysis stage need ensure only the attainment of the first target, i.e., a high degree of controllability. The reasons are delineated below.

a. The controllability of a synthesized network depends on the interconnections among the streams, i.e., the entire network structure. Often, a single inappropriate match may cause more than one intensive disturbance propagation through the network. This is detrimental to the controllability of the synthesized

network as discussed in the Section 3.1.2. Thus, stream match recommendations for controllability need be made prior to the network generation. For this purpose, the process data, i.e., the disturbance levels of stream inlet conditions and the precision levels for controlling stream target temperatures, are required apart from the source/target temperatures of streams and their heat capacity flowrates.

b. The MER and $U_{min,MER}$ are predicted by the pinch design method (see, e.g., Linnhoff et al., 1982). This method, in conjunction with the *hot-end match rule*, *cold-end match rule* , and *elimination strategy*, always enables us to attain these two targets if the backtracking technique is employed at the network invention stage. Therefore, no stream match recommendations are required for reaching the targets of MER and $U < U_{min,MER}$.

c. It is almost impossible to generate match recommendations for backtracking minimization. If a network generation is regarded as the construction of a search tree as in Chapter 1, the initial node, or the first level, of the tree represents an empty network (i.e., only a number of streams), and the final level of nodes a set of complete networks; the nodes between them are incomplete networks. Stream/stream matching generates the arc between

any two nodes. At the first several levels, it is arduous to predict arcs minimizing backtracking. The farther apart the node from the final nodes, the more difficult the identification of such arcs. Hence, there is no reason to make stream match recommendations for backtracking reduction at the preanalysis stage; instead, the backtracking minimization should be attempted at the network invention stage following the preanalysis stage.

3.1.2 Classification of Disturbance Propagations

Obviously, if the inlets of streams are not disturbed, the controllability of a synthesized network need not be our concern. However, the stream source temperatures and heat capacity flowrates almost always experience fluctuations because of the changes in the environmental conditions. The resultant disturbances will affect the stability of the stream target temperatures. Since the streams are usually highly interconnected through heat exchangers in the synthesized network, a disturbance tends to propagate through it; naturally, this is detrimental to the stability of the network. The more intensive the disturbance propagations, the higher the instability of the network. For convenience, it is highly desirable that the disturbance propagations be classified.

The disturbances originating from an inlet propagates through a HEN strictly toward downstream directions (Linnhoff and Kotjabasakis, 1986). However, the effect of this disturbance on the stream target temperature depends on its distance from the inlet, or the "downstream-path length". Consequently, the disturbance propagations can be classified according to the downstream-path lengths as depicted in the modified grid diagram, Fig. 3-2. In this figure, the level of a temperature disturbance is indicated by the number of solid circles, "●"'s, and the level of a heat capacity flowrate disturbance by the number of empty circles, "o"'s. The greater the number of circles, the more intensive the disturbance. The precision level for controlling the target temperature of a stream is indicated by the number of triangles, "▲"'s. The greater the number of triangles at the outlet of a stream, the higher the precision level for its control.

Type-1 propagation. Two classes of propagations lead to this *type-1 propagation*. One is from the inlet of a stream to the outlet of the same stream (Fig. 3-3-a), and the other is from the inlet of a stream to the outlet of another stream (Fig. 3-3-b). In both figures, the dashed lines indicate downstream paths along which the disturbances propagate. The *type-1 propagation* involves either one stream or a pair of streams linked directly.

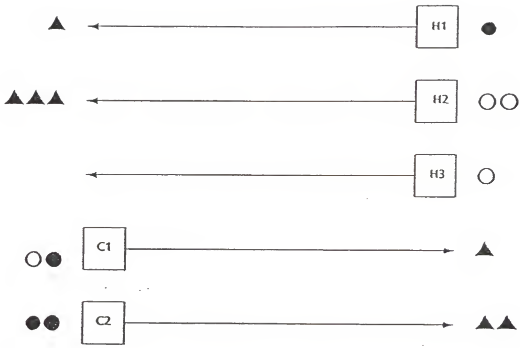
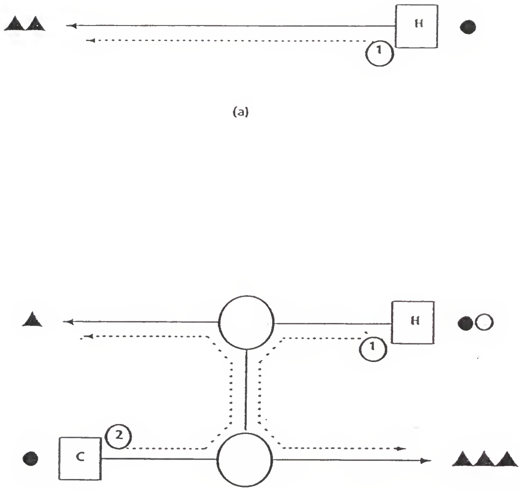


Figure 3-2 Grid diagram for a five-streams design problem.



(a)

(b)

Figure 3-3 Type-1 disturbance propagation.

Type-2 propagation. Figure 3-4 illustrates a *type-2 propagation,* where a disturbance propagates from the inlet of hot stream H1, through exchangers 1 and 2, to the outlet of hot stream H2. The downstream path is shown by a dashed line. Note that the *type-2 propagation* involves two matches.

Type-3 propagation. A *type-3 propagation* passes through three exchangers as indicated in Fig. 3-5 by a dashed line. Specifically, it is initiated at the inlet of hot stream H1, propagates through exchangers 1, 2, and 3, and eventually reaches the outlet of hot stream H2.

Type-∞ propagation. When a disturbance occurs at the inlet of a stream and propagates through numerous exchangers before reaching an outlet, its effect will be dissipated. The longer the downstream path, the greater the extent of dissipation. When this type of disturbance propagation involves more than three exchangers, we term it a *type-∞ propagation;* this is illustrated in Fig. 3-6-a with four matches. Obviously, if no direct and indirect linkages exist between two streams through heat exchangers, no disturbance propagates between them. This is almost equivalent to the case where the disturbance of a stream propagates to the outlet of another stream through an infinite number of exchangers. For convenience, therefore, the lack of disturbance propagation between two

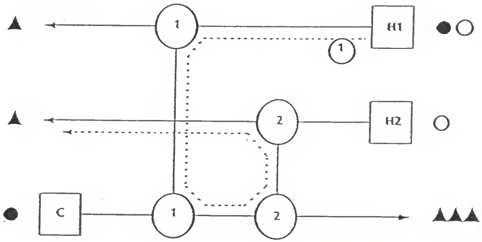


Figure 3-4 Type-2 disturbance propagation.

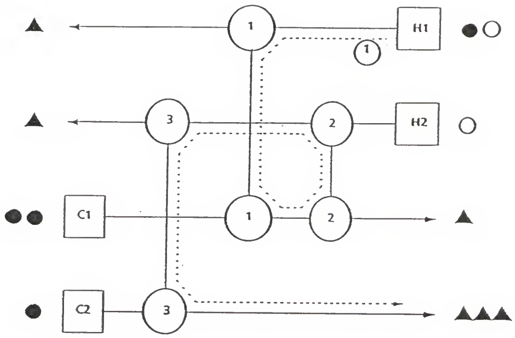
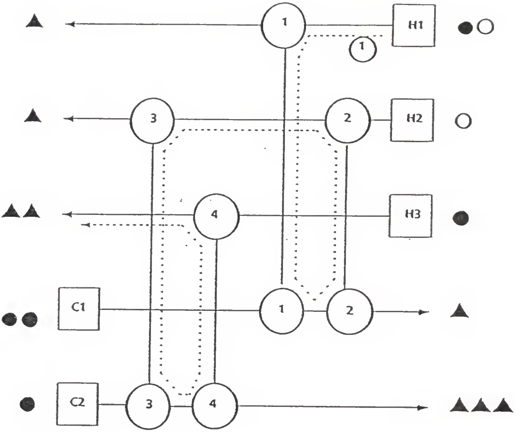


Figure 3-5 Type-3 disturbance propagation.



(a)

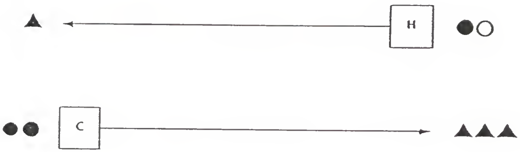
Figure 3-6 Type-oo disturbance propagation.

streams as indicated in Fig. 3-6-b can be regarded as a *type-∞ propagation*.

3.1.3 Rules for Stream Match Recommendations

If all streams are heated (or cooled) to their target temperatures only by heaters (or coolers) in HEN synthesis, there is no need to interconnect the streams (Fig. 3-7). However, it gives rise to zero energy recovery, which is undesirable. The stream match recommendations are made to minimize formation of undesirable interconnections, which intensify propagation of disturbances among the streams. The strategies for making these recommendations are as follows:

Optimal placement of the utility units (heaters and coolers). If a stream is heated (or cooled) by a heater (or a cooler), its output temperature can be readily controlled because the flowrate of a utility stream can be adjusted independently without affecting other streams. In Fig. 3-8, hot stream H1 is connected to cold stream C2 through exchanger 3. Although an intensive disturbance appears at the inlet of cold stream C2, the target temperature of hot stream H1 can be controlled readily because of cooler C.



(b)

Figure 3-6 Type-oo disturbance propagation.

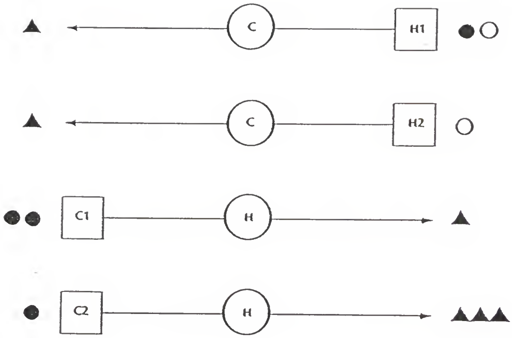


Figure 3-7 Network with zero energy recovery.

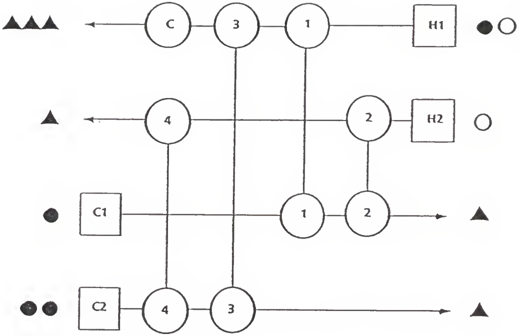


Figure 3-8 Correct placement of a cooler.

Prevention of formation of interconnections through which intensive disturbances propagate to streams whose target temperatures require relatively stringent control. Figure 3-9 depicts an example where no heater is required. Obviously, the match between hot stream H1 and cold stream C1 through exchanger 1 should be prevented; otherwise, it would be difficult to control the target temperature of hot stream H1 when cold stream C1 experiences an intensive disturbance.

Creation of interconnections through which intensive disturbances propagate to streams whose target temperatures require relative loose control. The HEN synthesis problem depicted in Fig. 3-10 poses the same problem as that posed by Fig. 3-9. Note, however, that these two figures exhibit different matches. In Fig. 3-10, cold stream C1 is matched with hot stream H2 whose target temperature need not be controlled very precisely. Note that no downstream path exists from cold stream C1 to hot stream H1.

The strategies for stream match recommendations can be translated into the following four rules.

a. Heater-placement rule

Place a heater on the hot end of the cold stream whose target temperature must be controlled most precisely among the unmatched (yet-to-be matched) cold streams.

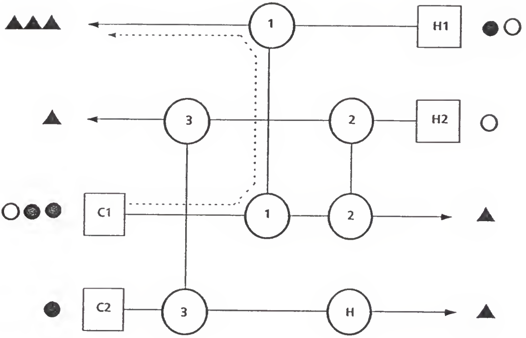


Figure 3-9 Downstream path from the inlet of cold stream C1 to the outlet of hot stream H1.

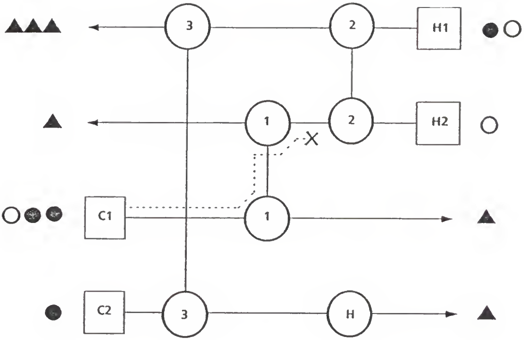


Figure 3-10 No downstream path from the inlet of cold stream C1 to the outlet of hot stream H1.

b. Cooler-placement rule

Place a cooler on the cold end of the hot stream whose target temperature must be controlled most precisely among the unmatched (yet-to-be matched) hot streams.

c. Match-disallowing rule

Disallow a match between a stream experiencing an intensive disturbance at its inlet and another stream whose target temperature need be controlled precisely, if the match gives rise to a type-1 or type-2 propagation.

d. Propagation-diverting rule

Make a match between a stream experiencing an intensive disturbance at its inlet and another stream whose target temperature need not be controlled precisely, if the match gives rise to a type-1 propagation.

It should be pointed out that not all interconnections need be considered at the preanalysis stage, because insufficient information is available to identify all interconnections at this stage. In reality, it is not necessary to do so because a strategy for controlling weak or unimportant disturbance propagations can be readily devised at the control system design phase.

3.2 HEURISTIC RULES FOR STREAM MATCH SELECTION

A set of heuristic rules for stream match selection are required for rapidly locating a superior network configuration. The requirements for selecting stream matches need be examined prior to the development of these rules.

3.2.1 Requirement for Stream Match Selection

Heuristic strategies for HEN generation must lead to sequential matching of streams, i.e., the streams are matched stepwisely. Such matching of streams is superior to the simultaneous matching of streams from the standpoint of analyzing and modifying the resultant network. Note that each stream match must be related to at least one of the synthesis targets, i.e., MER, $U < U_{min,MER}$, high degree of controllability, and minimum backtracking. However, the heuristic rules for stream match selection are required only for ensuring the last two targets. The reasons are delineated as follows:

a. As stated in Section 3.1, the stream match recommendations for the controllability need be made at the preanalysis stage. Nevertheless, these recommendations do

not encompass all requirements for the controllability, because of insufficient information available at this stage. In addition, the rationality of the recommendations need be examined at the network invention stage. Not all the recommendations can be realized, and therefore, rules for enhancing the controllability are needed to guide the stream match selection.

b. There is no assurance that backtracking can be eliminated at the network invention stage. This is especially true for the first several matches in HEN generation. However, reasonable selection of a match type can at least reduce the possibility of the occurrence of dead-end situations. This will be discussed in detail in the succeeding subsection.

c. At the network invention stage, a HEN problem is divided into two parts by a pinch point. Thus, separately designing each part prevents heat from flowing across the pinch point, thereby ensuring the attainment of MER and $U < U_{min,MER}$, although the performance of the resultant network may not be superior, and its total cost may not be minimum. Therefore, no rules are required to ensure the MER and $U < U_{min,MER}$.

3.2.2 Rules for System Controllability

It appears that the system control performance is not taken into account at the network invention stage in any of the available synthesis methods. Thus, the resultant network may become difficult to control if a stream, whose inlet conditions are appreciably disturbed, and another stream, whose target temperature need be controlled precisely, are unduly interconnected. If this situation does occur at the network invention stage, it would be extremely difficult, if not impossible, to eliminate it at the network evolution stage. To eliminate or, at least, minimize undesirable interconnections among the streams from the standpoint of controllability, the following two rules are proposed.

a. Minimum-interconnection rule

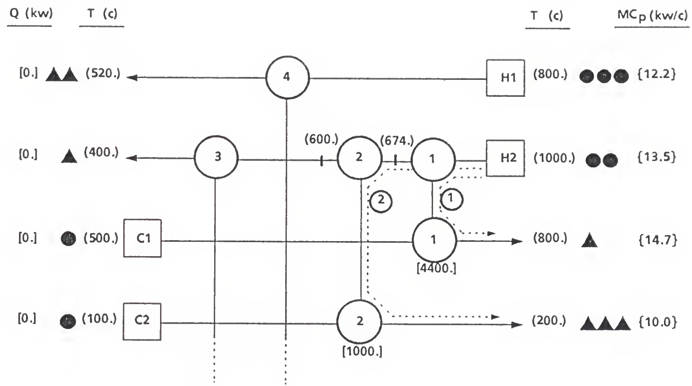
Avoid matching a stream, whose target temperature is to be controlled precisely, with a stream, whose source temperature and/or heat capacity flowrate is likely to experience severe fluctuations.

b. Hot/hot or cold/cold streams match rule

To prevent an undesirable interconnection (i.e., disturbance propagation), select a match between two similar streams (i.e., two hot

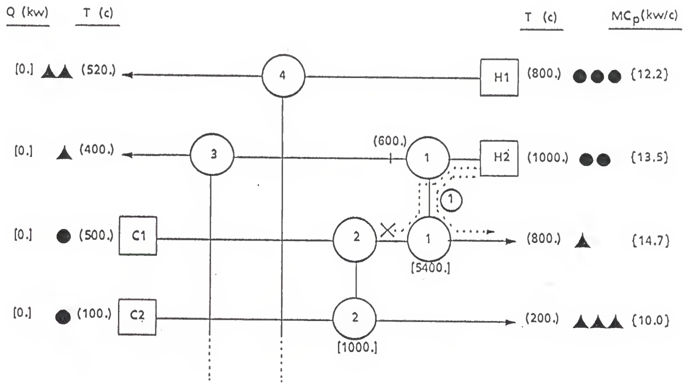
streams or two cold streams) if no alternate choice exists provided that the resultant increase in the cost is within an acceptable range.

Both rules are illustrated in Fig. 3-11. Suppose that the inlet temperature of hot stream H2 is constantly disturbed severely (three "●"'s appearing at its inlet), and that the outlet temperature of cold stream C2 is to be controlled very precisely (three "▲"'s appearing at its outlet). Also suppose that matches H2/C1 and H2/C2 have been generated as shown in Fig. 3-11-a; note that these matches have given rise to two downstream paths indicated by dotted lines 1 and 2. Path 2, originating at the inlet of hot stream H2, passing through exchangers 1 and 2, and finally reaching the outlet of cold stream C2, is undesirable. In fact, path 2 can be eliminated by the match through exchanger 2 as illustrated in Fig. 3-11-b. Obviously, the network in Fig. 3-11-b propagates disturbances less than that in Fig. 3-11-a, provided that other matches remain unchanged. However, the heat load of exchanger 1 is increased by 1000 kw, thereby resulting in increases in the heat transfer area and capital cost for the subnetwork, although the heat utilities and the number of HTU's remain unchanged. If the increase in the cost of the overall network is tolerable (e.g., within 1% ~ 5%),



(a) Conventional match between hot stream H2 and cold stream C2

Figure 3-11. Two different types of matches: hot/cold match vs. cold/cold match.



(b) Cold/cold stream match between C1 and C2

Figure 3-11. Two different types of matches: hot/cold match vs. cold/cold match.

the network in Fig. 3-11-b may be more acceptable than that in Fig. 3-11-a.

3.2.3 Rule for Backtracking Reduction

Jezowski and Hahne (1986) have reported that, in eliminating one of the two streams by matching them either at their hot or cold ends by resorting to rules HS-1h/1c and HS-2h/2c, four match options are generated. These match options can be divided into type-1 and type-2 matches (Fig. 3-12). The former leaves the cold end of a hot stream to be matched in a future step when $Q_h > Q_c$, or leaves the hot end of a cold stream to be matched in a future step when $Q_h < Q_c$. The latter leaves the hot end of a hot stream to be matched in a future step when $Q_h > Q_c$, or leaves the cold end of a cold stream to be matched in a future step when $Q_h < Q_c$.

Note that if a pair of streams can be matched, the resultant heat transfer area from the type-1 match is less than that from the type-2 match. Nevertheless, the reduction in the cost of an individual HTU does not necessarily lead to that of the overall network. A type-1 match selection may increase the total cost, while a type-2

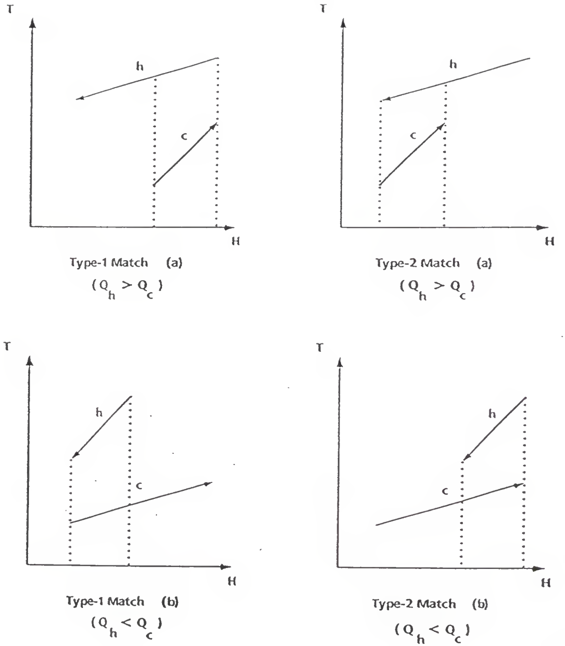


Figure 3-12. Two types of stream matches.

match selection may decrease it, depending on the total heat transfer area and its distribution although the number of HTU's is unchanged. Furthermore, the type-2 match always reduces the possibility of dead-end situations, thereby accelerating solution. The following rule facilitates the trade-off among controllability, MER and U_{min}.

Leaving-end-unmatched rule

Select a match, while leaving the hot end of a hot stream or the cold end of a cold stream unmatched, if the match is not detrimental to the controllability of the synthesized network and does not increase the total cost.

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CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions reached in the present thesis are recapitulated. This is followed by the presentation of recommendations for the future work.

4.1 CONCLUSIONS

The heuristic approach in HEN synthesis is in reality a heuristic rule/strategy-oriented approach. The heuristic rules and strategies involved in this approach (or heuristics for short) are mainly based on: (i) the principles of thermodynamics, (ii) the designer's experience in rapidly identifying feasible networks, and (iii) the evaluation of economic efficiency and control performance of the synthesized networks. These heuristics provide a series of guidelines for network generation. Moreover, the heuristics effectively represent incomplete data, imprecise information, and uncertain knowledge always involved in HEN synthesis. Thus, there is every reason to believe that the heuristic approach is attractive and effective.

In the present work, the importance of further developing the heuristic approach is presented. The reasons why relatively little progress has been made in its application are: (i) the excessive redundancy in available heuristics, (ii) the lack of effective heuristic rules leading to the reduction in the total cost, enhancement of system performance, and minimization of backtracking in network construction, (iii) the inadequacy in developing heuristics for stream match recommendations at the preanalysis stage, and (iv) the ignorance of efficient heuristic strategies for organizing and manipulating the heuristic rules.

The available heuristics for HEN synthesis have been exhaustively analyzed for the purpose of eliminating redundant ones. The results of analysis are rather surprising; among 17 available heuristics, only 2 are meaningful and necessary. These two rules have been restated as the *hot-end match* and *cold-end match rules*. The elimination of redundant heuristics leads to a significant shrinkage in the search space in HEN generation.

Two sets of new heuristic rules have been developed. One is for stream match recommendation at the preanalysis stage; it includes the *heater-placement*, *cooler-placement*, *match-disallowing*, and *propagation-diverting rules*. The

other is for stream match selection at the network invention stage; it includes the *minimum-interconnection*, *hot/hot or cold/cold stream match*, and *leaving-end-unmatched rules*. These two sets of rules facilitate the attainment of the targets of HEN synthesis, i.e., MER, $U < U_{min,MER}$, a high degree of controllability, and minimum backtracking.

A distinct feature of the new rules is the consideration of controllability of the resultant network, which hitherto has mostly been neglected. The advantage of incorporating the controllability as a criterion is that the resultant network structure increases its stability, thereby simplifying the control system designed for it. To facilitate examination of the controllability, disturbances in the stream source temperatures and heat capacity flowrates, and levels of precision for controlling stream target temperatures are roughly classified into three groups. A slight difference in disturbances does not cause a large difference in stability of the network, and it is impossible to obtain accurate information about these disturbances and levels of precisions. Moreover, 4 types of disturbance propagations are identified, i.e., *type-1*, *type-2*, *type-3*, and *type-∞ propagations*. The classification of disturbances and levels of precision, and

the identification of types of disturbance propagations form the base of developing heuristic rules for enhancing controllability.

The new heuristic rules are illustrated with numerous examples. These examples amply demonstrate that feasible and at least near optimal networks can always be synthesized with the new heuristic rules developed in the present work.

It is worth noting that a HEN with a high degree of controllability is particularly useful for hazardous waste incineraton or similar plants. In such plants, large fluctuations almost always exist in the feed rate and in the properties; furthermore, the economic efficiency of the plants depends largely on energy recovery from the combustion products through heat exchanger networks.

4.2 RECOMMENDATIONS

The ultimate goal of HEN synthesis is to create an intelligent knowledge-based system which can be used to automatically generate with minimum effort networks having the MER, $U < U_{min,MER}$, and high degree of controllability. While the present work has laid a groundwork for this goal, the following tasks need be performed for complete development of such a system.

a. Heuristic rules for minimizing the total cost are required, because the MER and $U < U_{min,MER}$ do not give rise to the minimum total cost in general. The well-known 0.6 power rule for cost estimation of a network is a good approximation. It can serve as a starting point for developing the new rules (Huang and Fan, 1988a).

b. Heuristic strategies need be created, which represent the available knowledge for HEN synthesis at the conceptual level. These strategies will be employed to organize and manipulate the heuristic rules. For instance, the depth of search for stream match selection need be flexibly controlled in the light of the current incomplete network. This can be realized by a so-called controllable look-ahead N-step strategy (Huang *et al.*, 1988b)

c. Although different levels of disturbances of streams at the inlets and those of precision for controlling the stream target temperatures are identified, a representation scheme for guiding stream match selection need be developed by analyzing dynamic characteristics of the synthesized network. Such a scheme can be called the disturbance propagation matrix (Huang and Fan, 1988b).

d. A systematic synthesis procedure — the core of the intelligent knowledge-based system — should be realized by rationally organizing the heuristic rules (Huang and Fan, 1988b).

e. The heuristic rules for HEN synthesis need be fuzzified based on subjective judgement because they are derived from incomplete data, imprecise information, and uncertain knowledge. In addition, meta-rules, or the rules of rules, are required to resolve possible conflicts in the rule base. Obviously, the intelligent knowledge-based system must be a fuzzy expert system. The fuzzy rules constitute the rule base, and the heuristic strategies comprise the control strategies of this system (Huang <u>et al</u>., 1988b).

f. The intelligent knowledge-based system for HEN synthesis should be implemented in a multiple paradigm object-oriented knowledge programming system, e.g., the Knowledge Engineering Environment (KEE), that executes

under the Interlist-D environment on a Xerox 1108 or 1186 Artificial Intelligence workstation.

g. Although the present work is focussed on the HEN synthesis, it should be extended to the synthesis of entire process plants, such as hazardous waste incineration plants and power plants. It is belived that a HEN with a high degree of controllability can effectively recover energy from such plants if it is coupled to other energy recovery systems including cogeneration and district heating facilities.

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ANALYSIS AND DEVELOPMENT OF HEURISTIC STRATEGIES

IN HEAT EXCHANGER NETWORK SYNTHESIS

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ABSTRACT

Heat exchanger network (HEN) synthesis has drawn considerable attention in recent years, mainly because of the economic benefits derived from energy integration. Numerous methods have been developed to synthesize a HEN with the minimum total cost under steady-state conditions. An Artificial Intelligence technique, namely, the heuristic search approach, is involved in one of the methods.

In the present work, the importance of further developing the heuristic approach is presented. It is followed by a discussion of the reasons why relatively little progress has been made in its application.

The available heuristics for HEN synthesis have been analyzed exhaustively for the purpose of eliminating redundant ones. The results of analysis are rather surprising; among 17 available heuristics, only 2 are meaningful and necessary; these two rules have been restated. The elimination of redundant heuristics leads to a significant shrinkage in the search space in HEN generation.

Two sets of new heuristic rules have been developed. One is for stream match recommendation at the preanalysis stage, and the other is for stream match selection at the network invention stage. These two sets of rules

facilitate the attainment of the targets of HEN synthesis, including MER, $U < U_{min,MER}$, a high degree of controllability, and the minimum backtracking. A distinct feature of the new rules is the consideration of controllability of the resultant network, which hitherto has mostly been neglected. The advantage of incorporating the controllability as a criterion is that the resultant network structure increases its stability, thereby simplifying its control system.

To facilitate examination of the controllability, disturbances in the stream source temperatures and heat capacity flowrates, and levels of precision for controlling the stream target temperatures are roughly classified. Moreover, types of disturbance propagations are identified. The classification of disturbances and levels of precision, and the identification of types of disturbance propagations form the base of developing heuristic rules for enhancing controllability.

The new heuristic rules are illustrated with numerous examples. These examples amply demonstrate that feasible and at least near optimal networks can always be synthesized with new heuristic rules developed in the present work.